Cosmology from gravitational lensing
or: How I learned to keep worrying but love photometric redshifts

Daniel Gruen, Einstein Fellow @ SLAC

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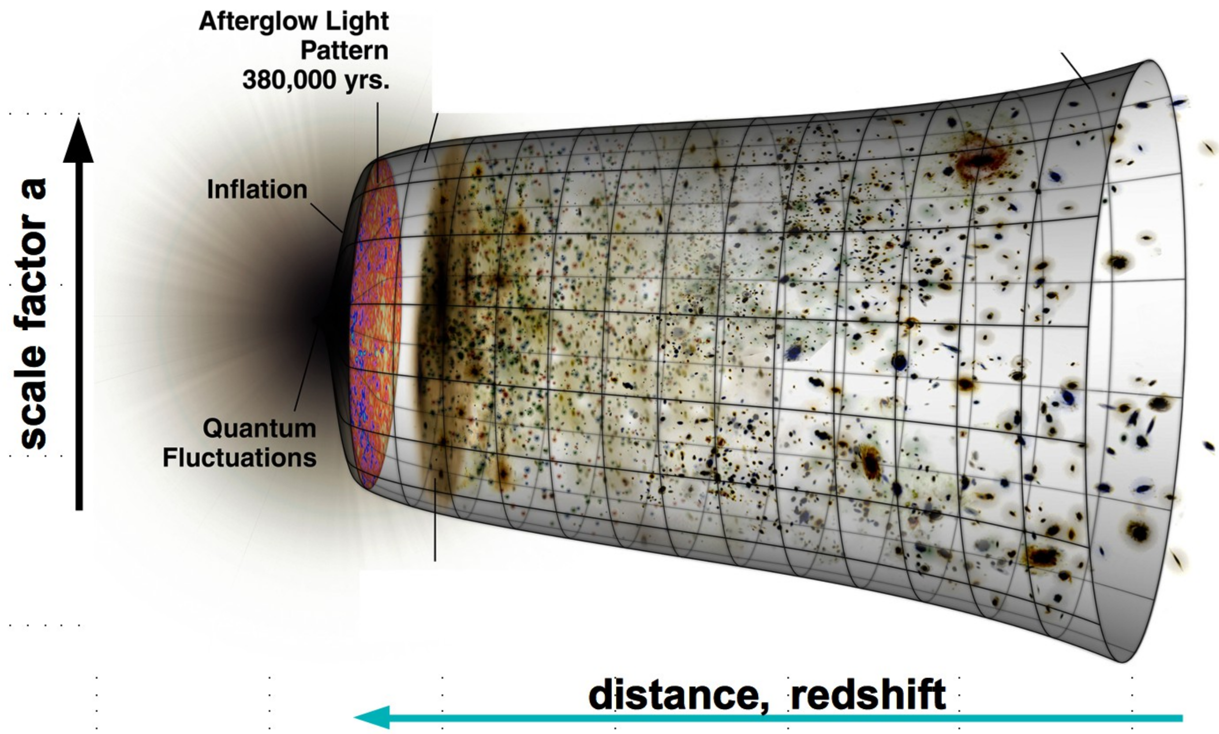
What goes up keeps getting faster!

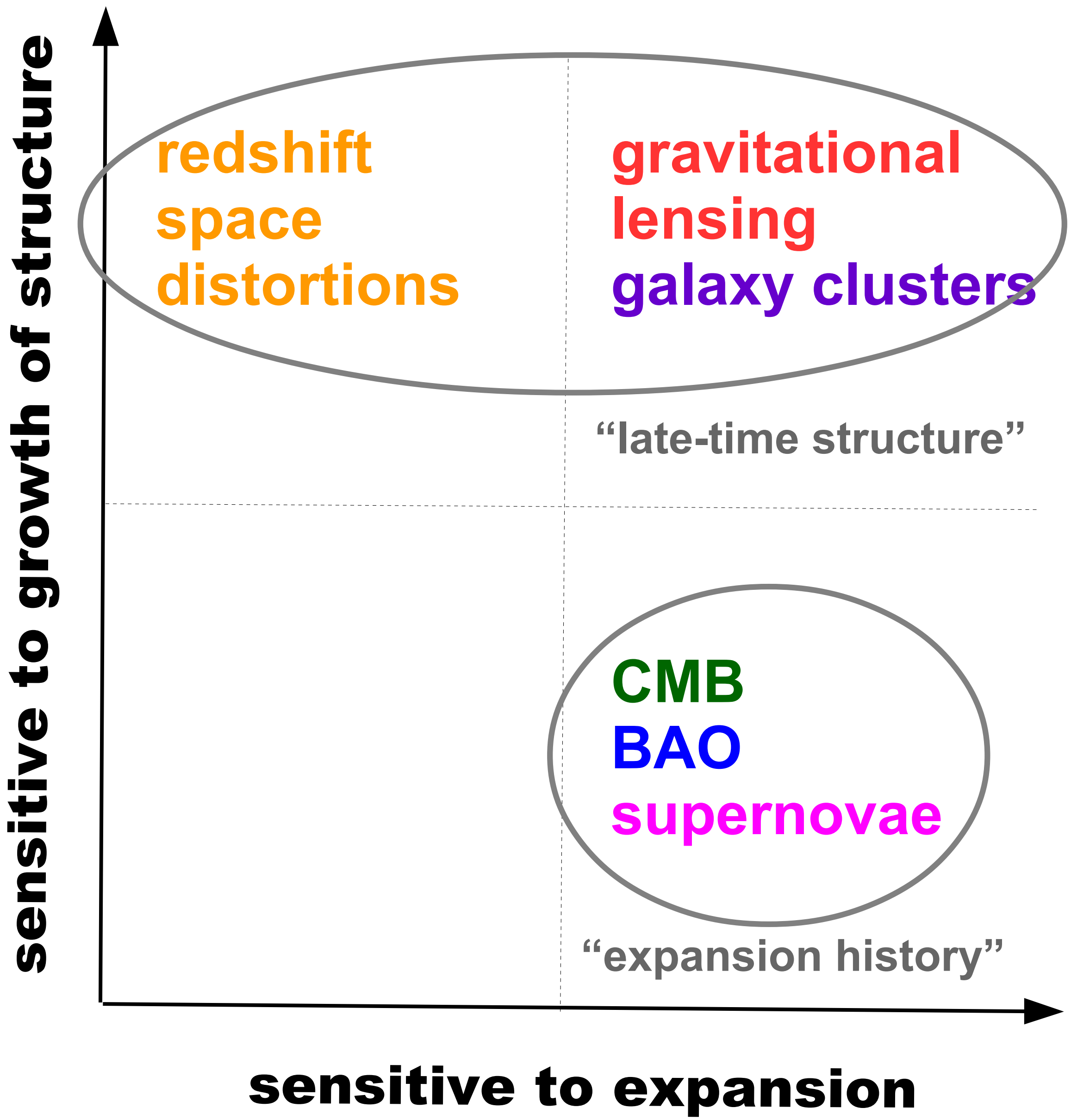
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

scale factor of Universe

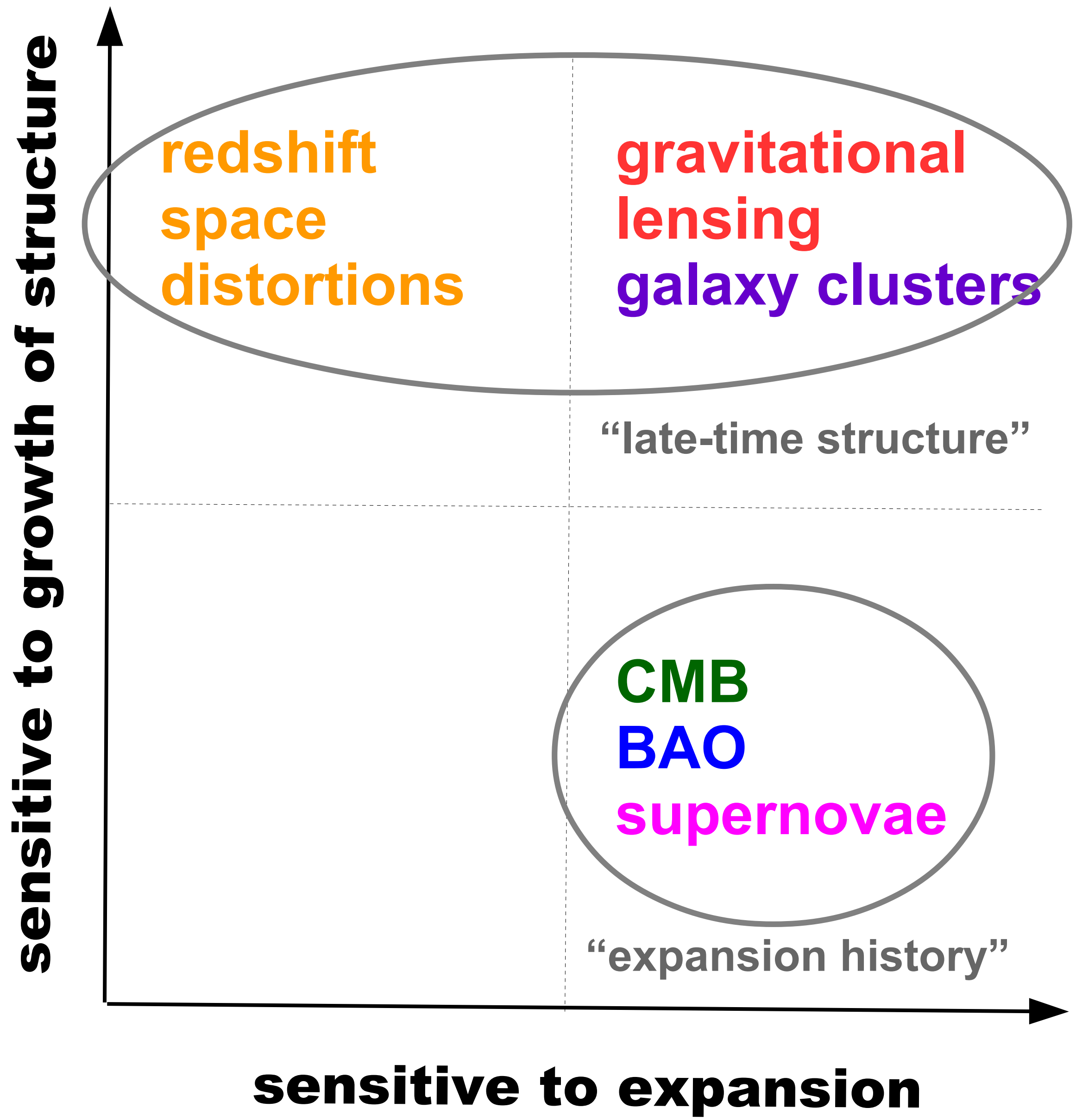
cosmological constant = vacuum energy = substance with negative pressure, “w= -1”



How to survey Dark Energy



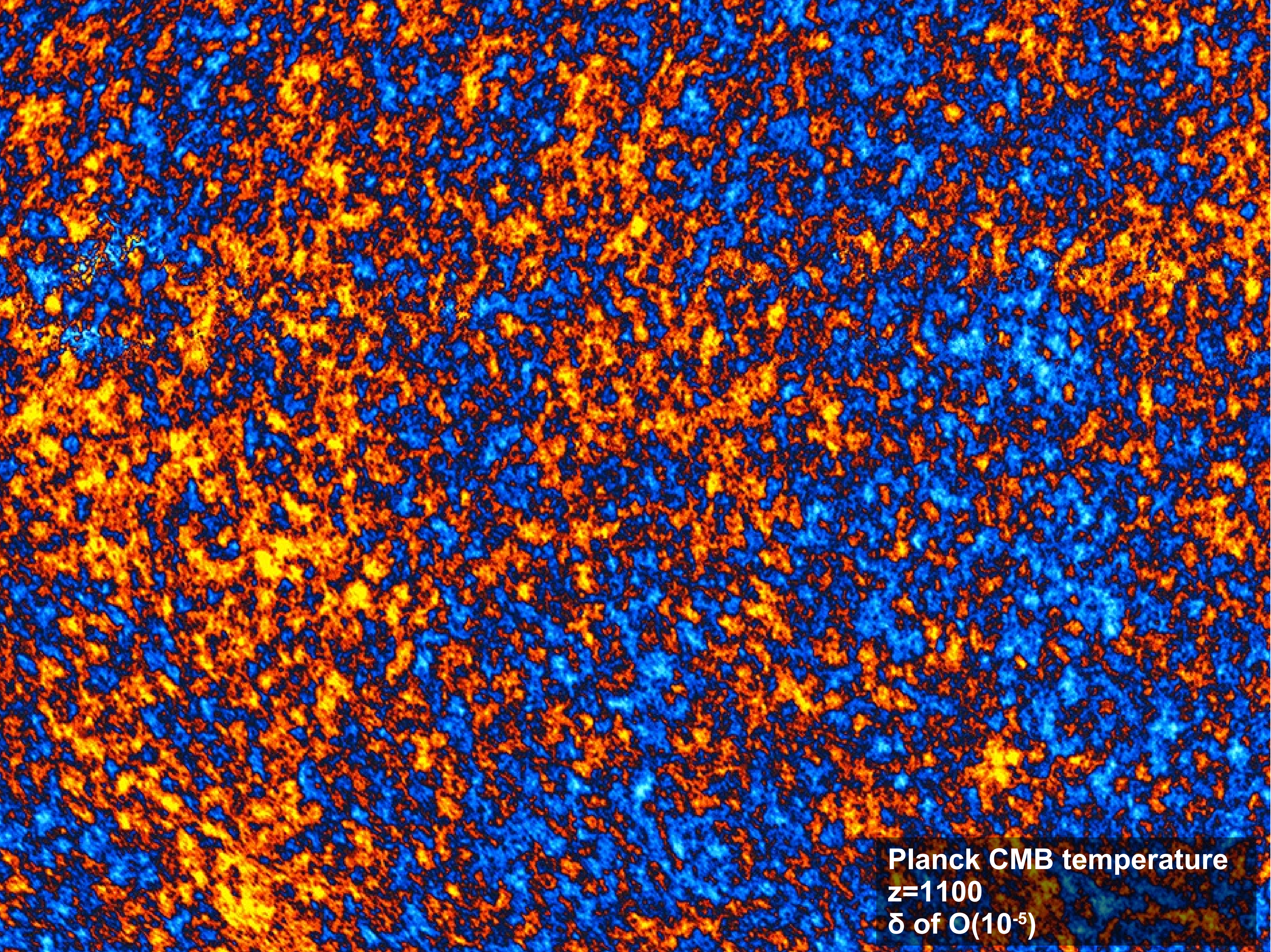
How to survey Dark Energy

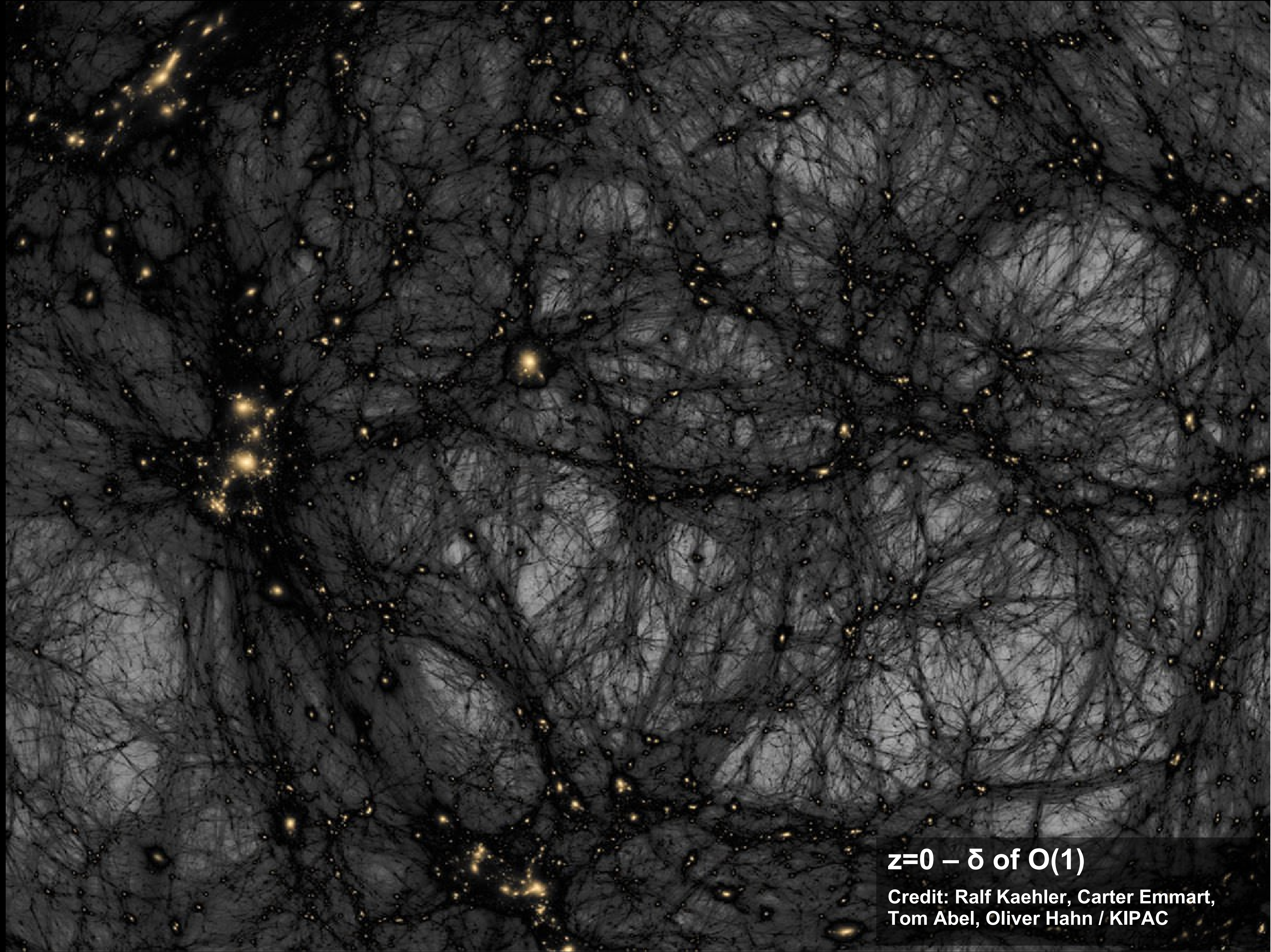


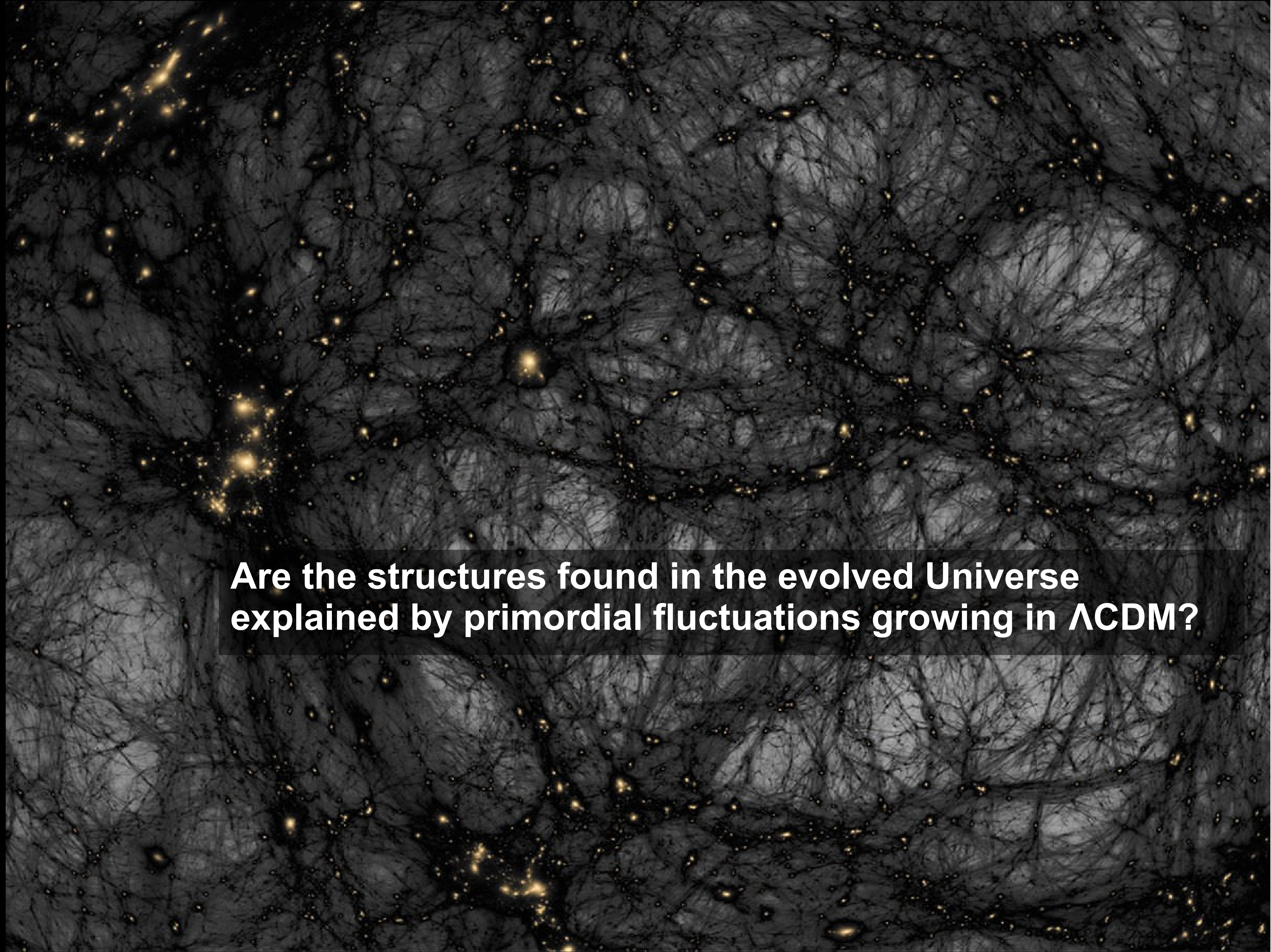
Expansion paints a consistent picture of a fiducial ΛCDM model.*

How about structure?

* if you don't count H_0


Planck CMB temperature
$z=1100$
δ of $O(10^{-5})$

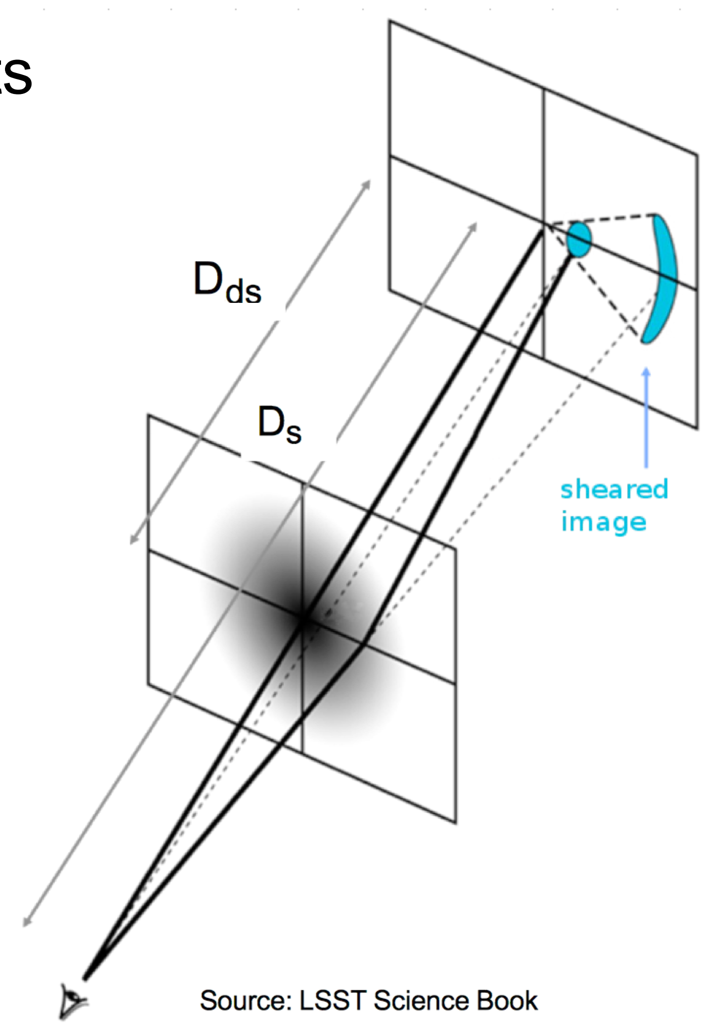

z=0 – δ of O(1)
Credit: Ralf Kaehler, Carter Emmart, Tom Abel, Oliver Hahn / KIPAC


Are the structures found in the evolved Universe
explained by primordial fluctuations growing in ΛCDM?

Gravitational lensing

- When light passes massive structures, it feels gravity and its path gets bent
- This causes shifting, and magnification, and <u>shearing</u> of the galaxy image

$$\gamma_t(\theta) = \langle \kappa(\theta') \rangle_{\theta' < \theta} - \kappa(\theta)$$
$$\kappa = \Sigma / \left[\frac{c^2}{4\pi G} \frac{D_\mathrm{s}}{D_\mathrm{d} D_\mathrm{ds}} \right]$$



Source: LSST Science Book

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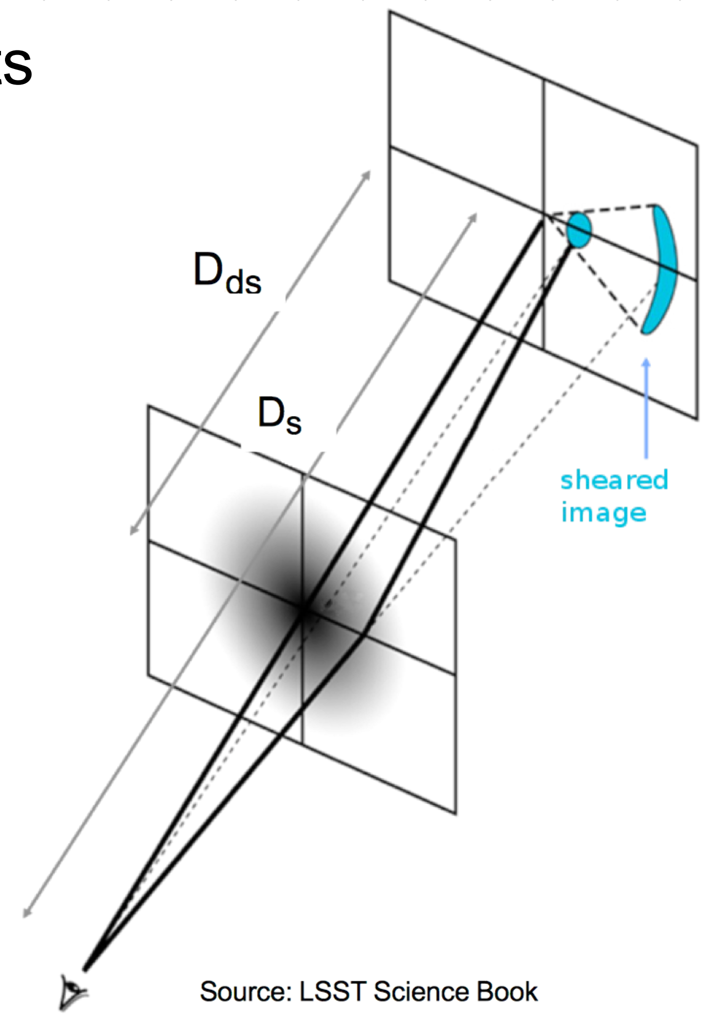

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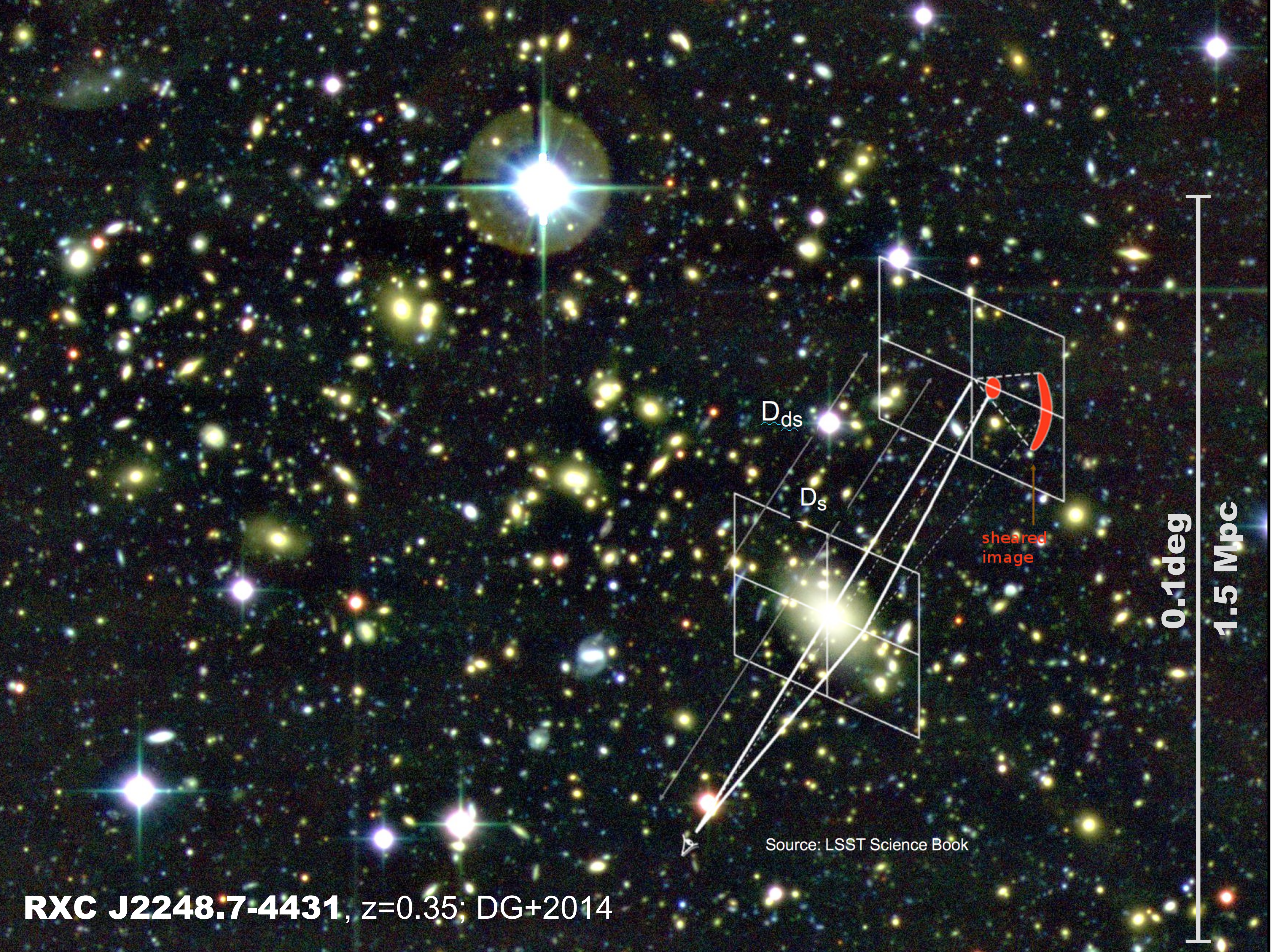
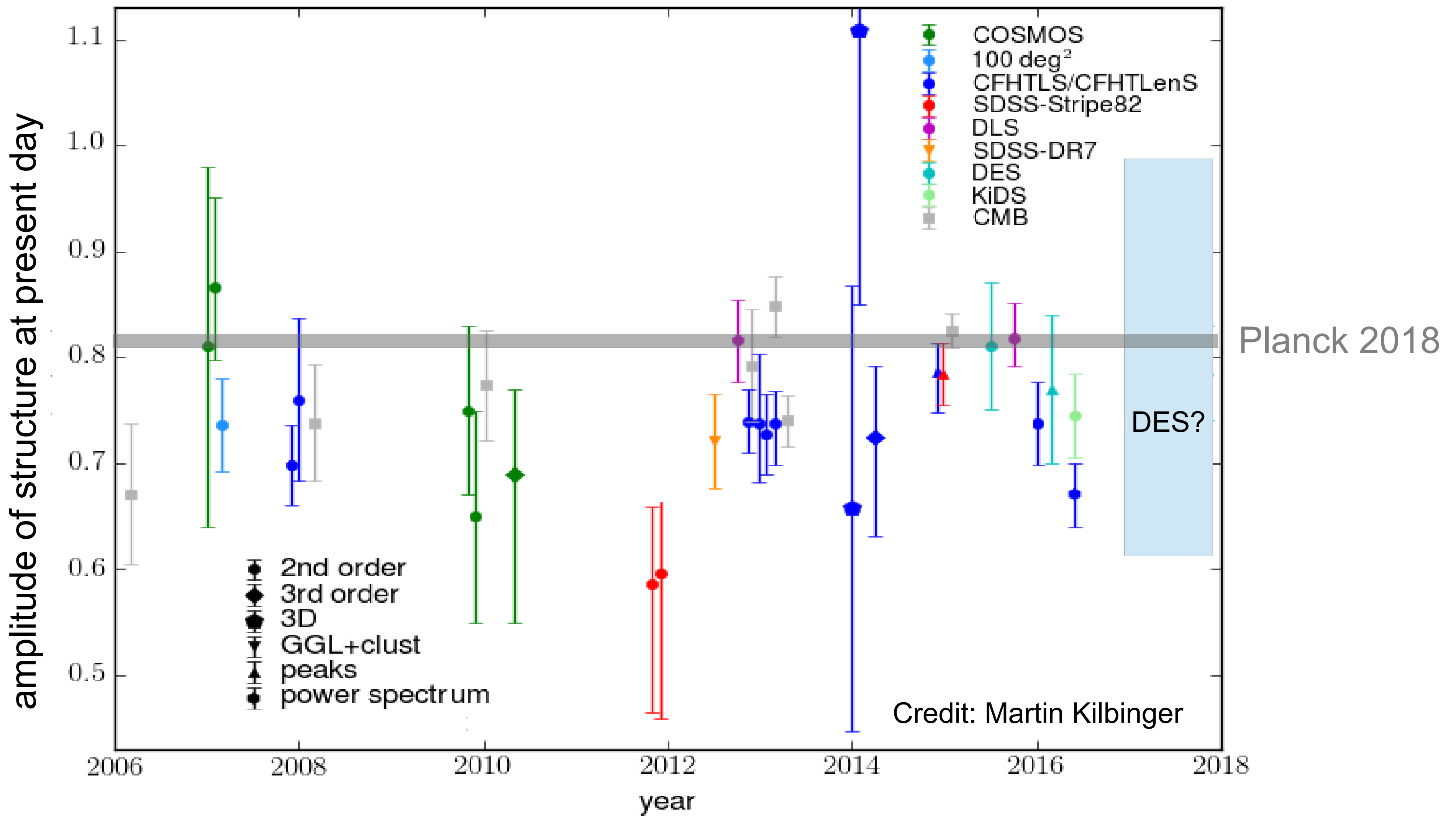
Need to measure galaxy shapes and redshift distributions



D_ds
D_s
sheared image
Source: LSST Science Book
0.1deg
1.5 Mpc
RXC J2248.7-4431, z=0.35; DG+2014

Is there evidence for tension from gravitational lensing?



- recent studies have claimed 2-3σ offset from Planck CMB in Ω_m-σ_8

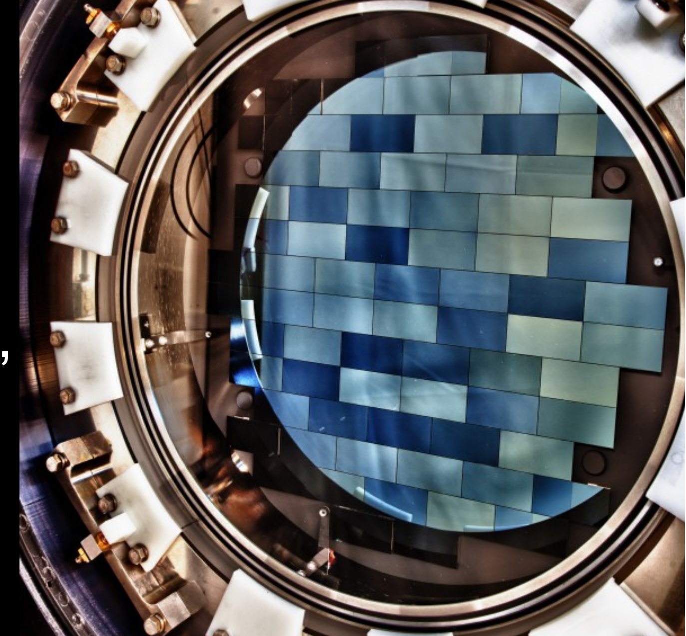
  but see Troxel&Krause, DG+2018
- interpretations differ – statistical fluke, systematics, crack in ΛCDM?

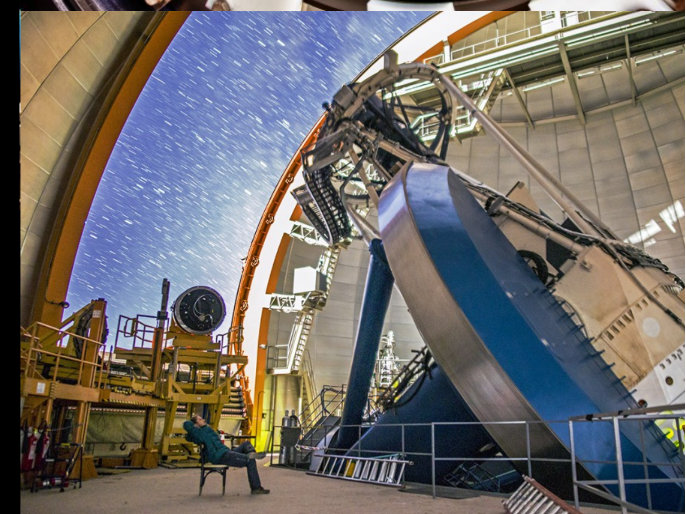
The Dark Energy Survey

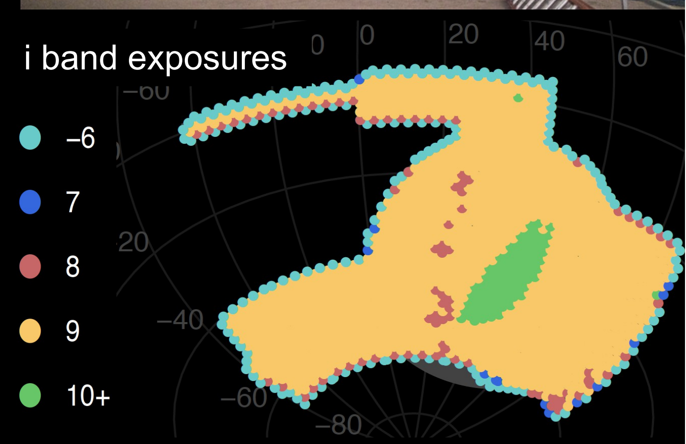
- 5000 sq. deg. survey in grizY from Blanco @ CTIO, 10 exposures, 5.5 years, >400 scientists
- Primary goal: dark energy equation of state
- Probes: Large scale structure, Supernovae,
  Cluster counts, Gravitational lensing
- Status:
  - Y1 (1500 sq. deg, 40% depth):
    key results published / in internal review
  - Y3 (5000 sq. deg, 50% depth):
    data processed, vetting catalogs
  - Y5: data taking finished (90% depth)
  - Y6: homogeneous survey at planned depth

  basic Y3 data released 01/10/18

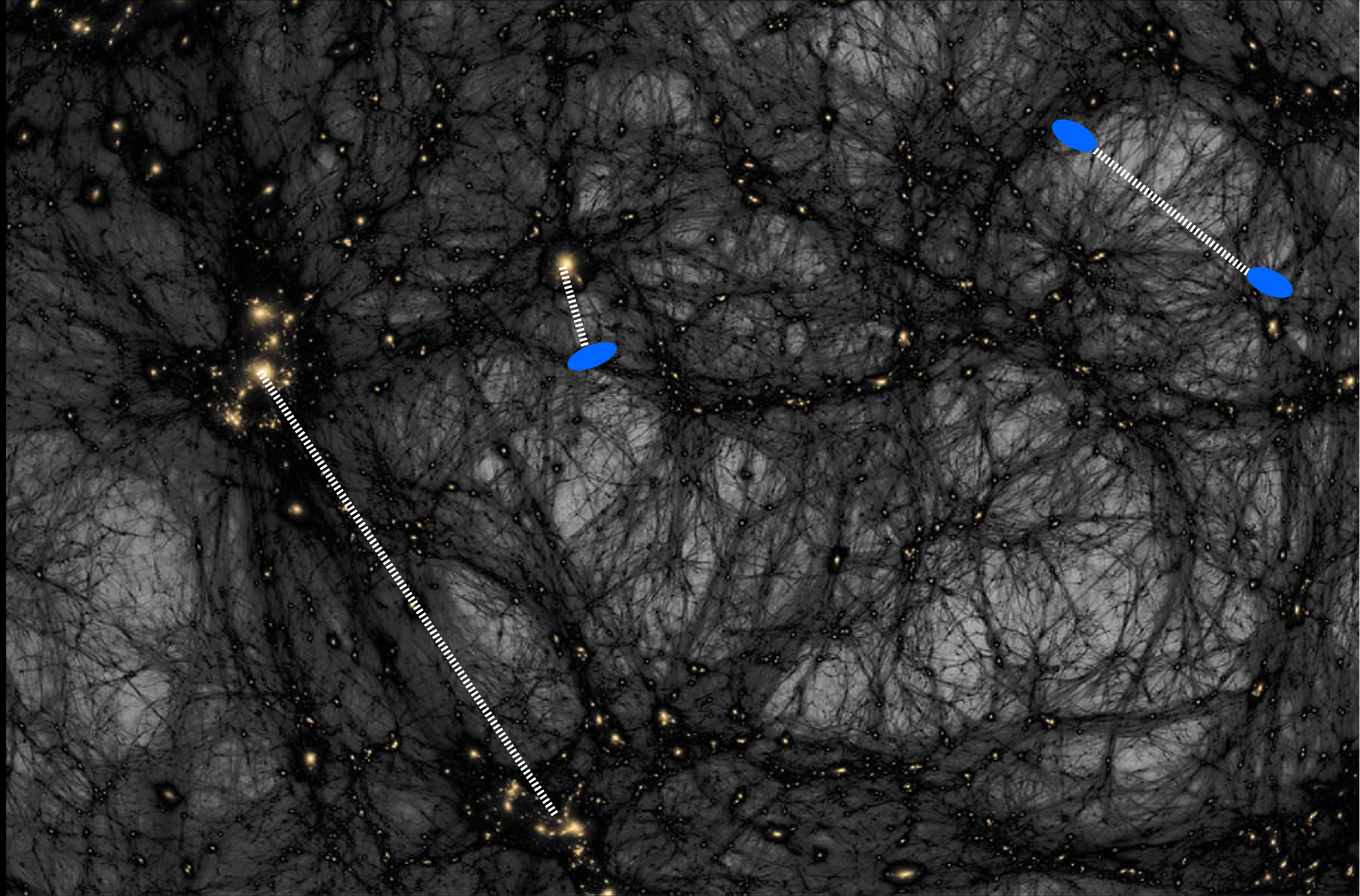
  full Y1 value added data released 10/01/18

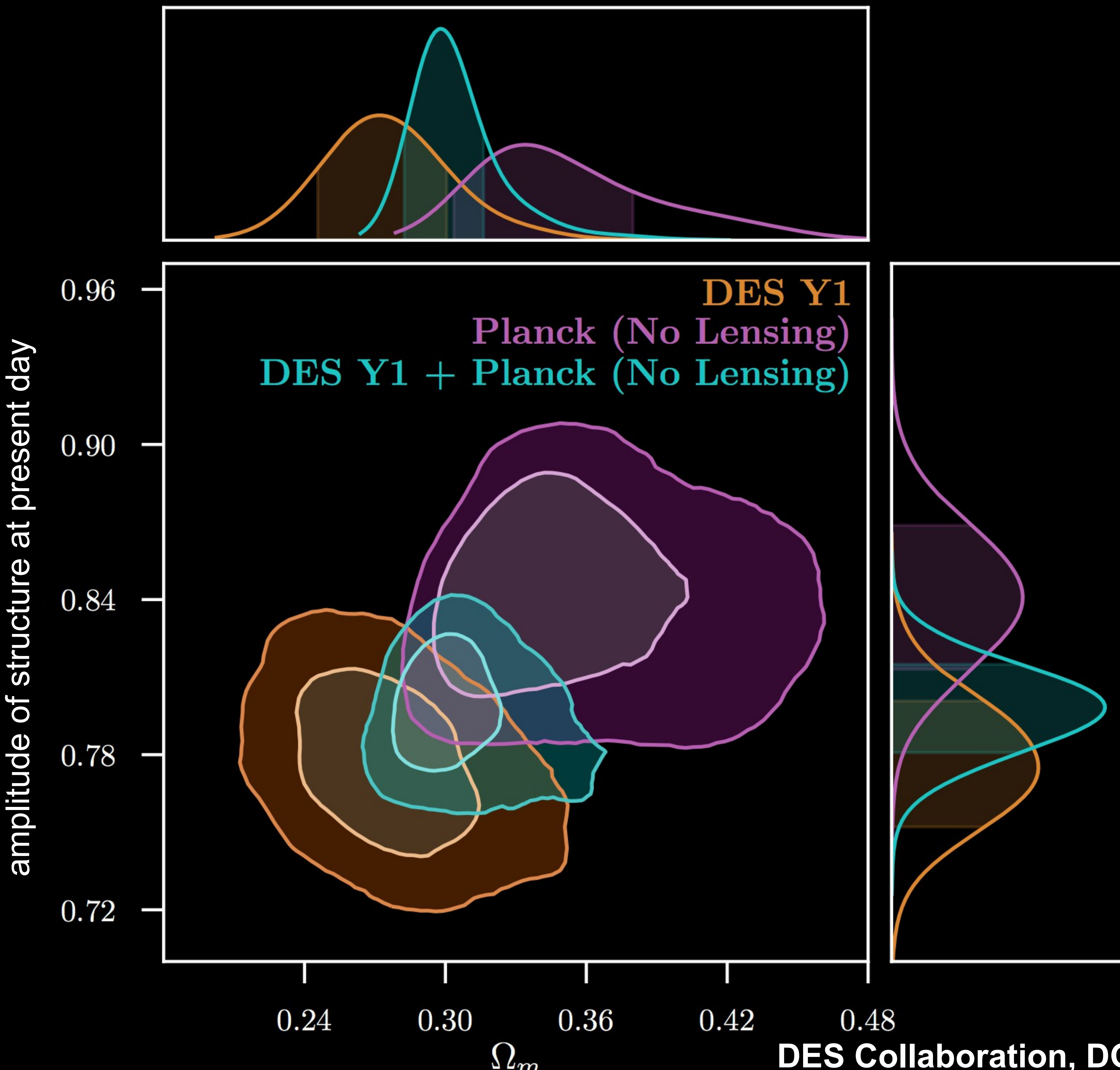




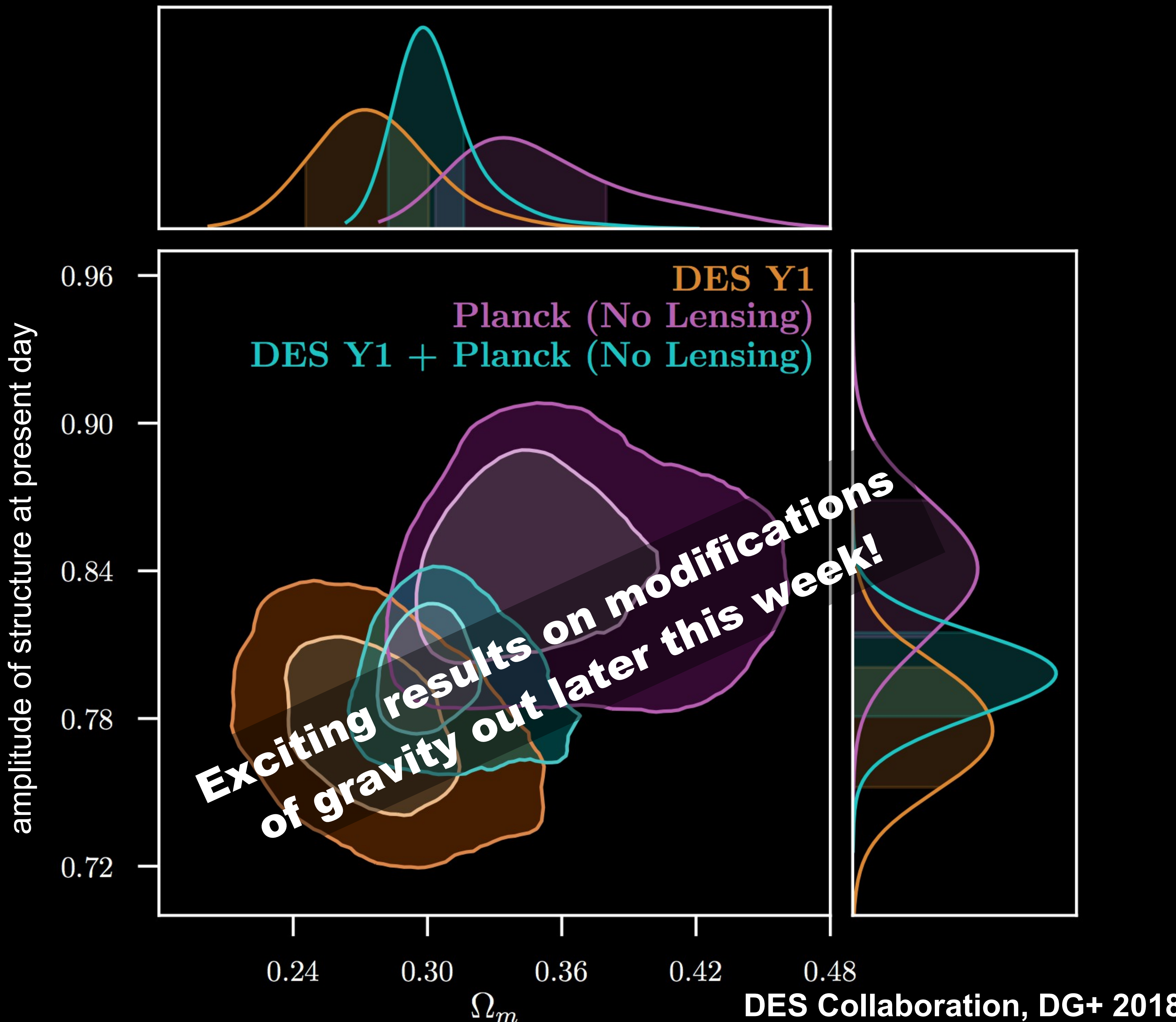


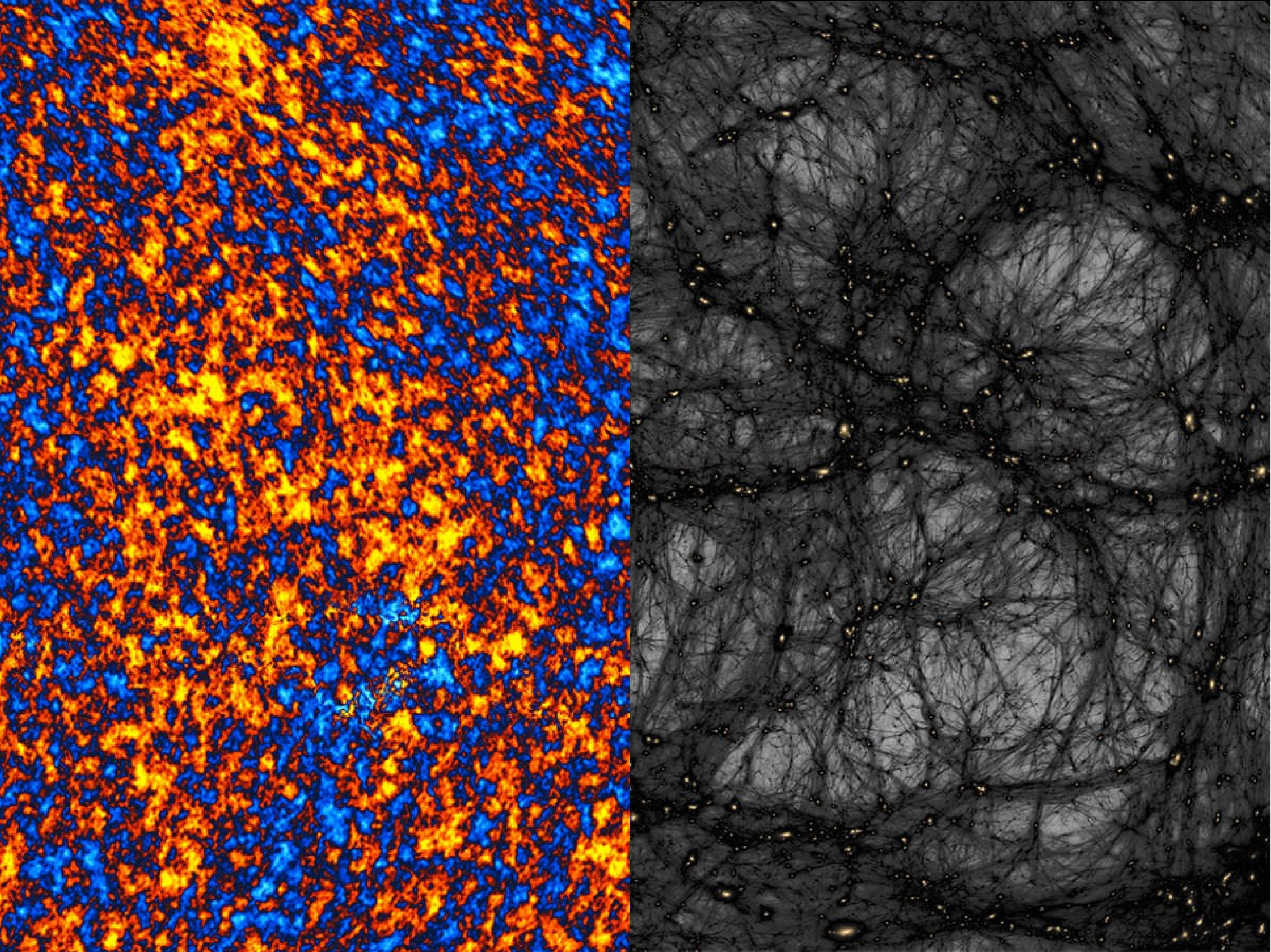
1) Cosmology from two-point correlations



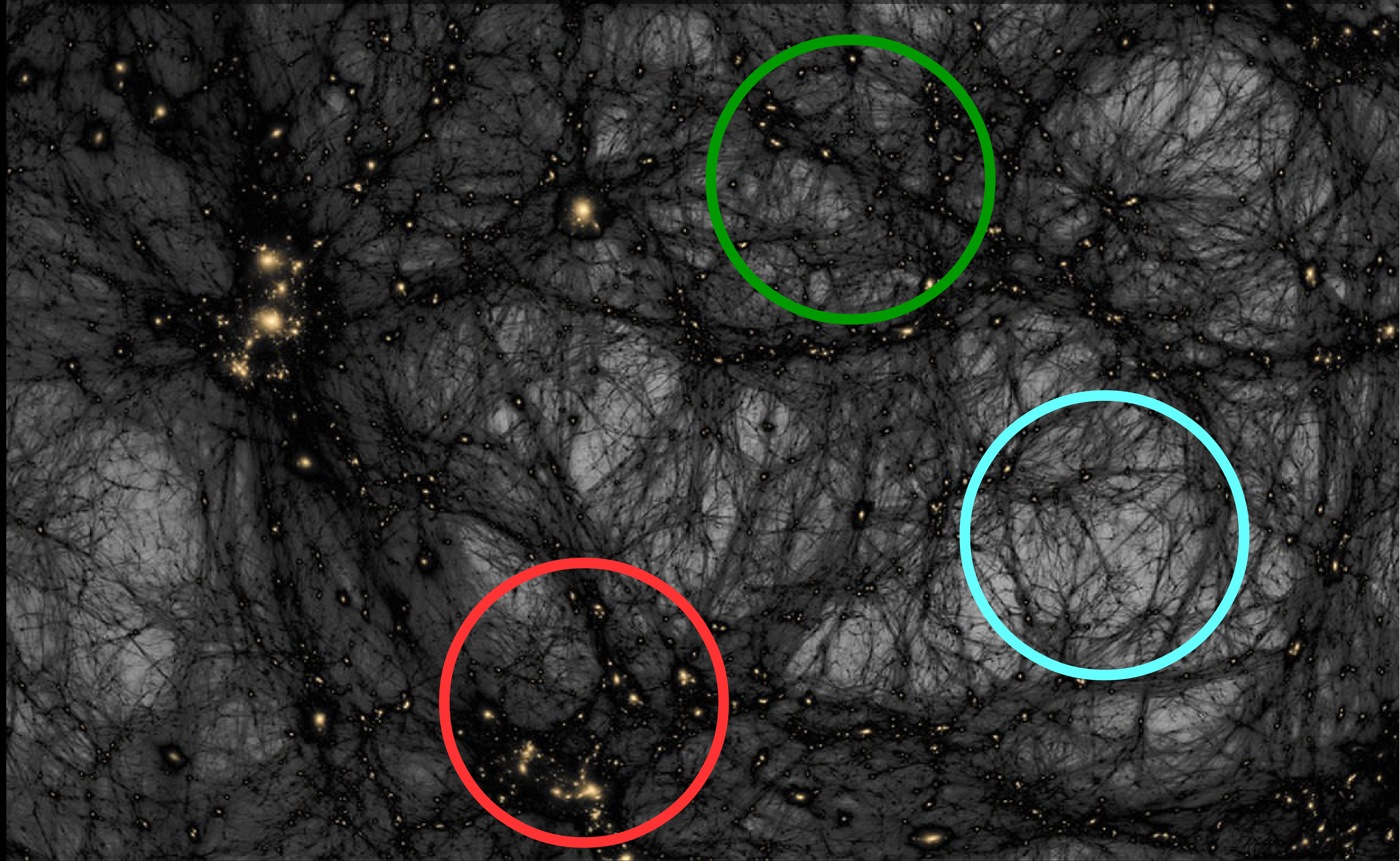


DES Collaboration, DG+ 2018


DES Y1
Planck (No Lensing)
DES Y1 + Planck (No Lensing)
amplitude of structure at present day
0.96
0.90
0.84
0.78
0.72
0.24
0.30
0.36
0.42
0.48
Ω_m
Exciting results on modifications of gravity out later this week!
DES Collaboration, DG+ 2018



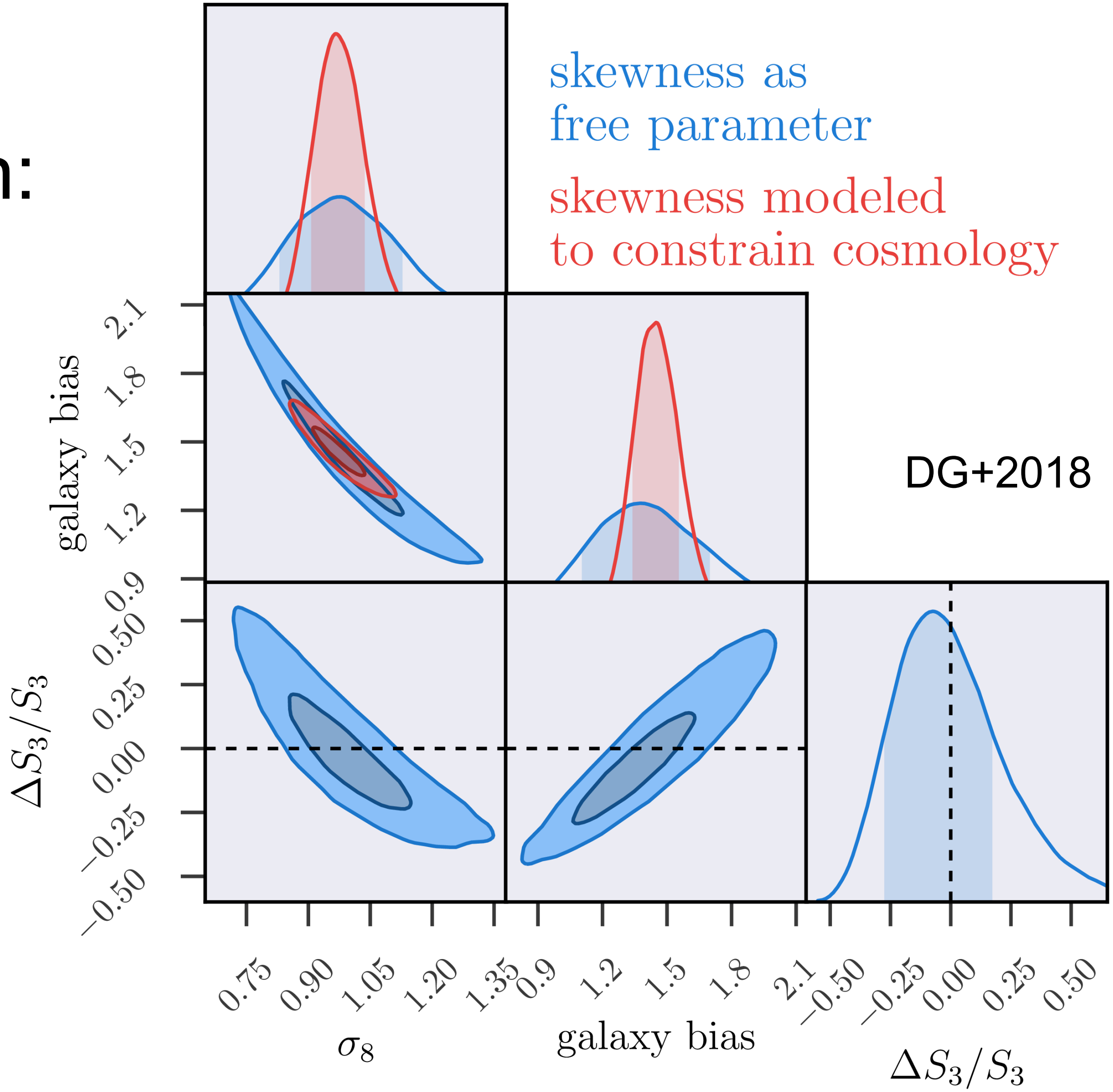
2) Measuring the non-Gaussian PDF of matter density



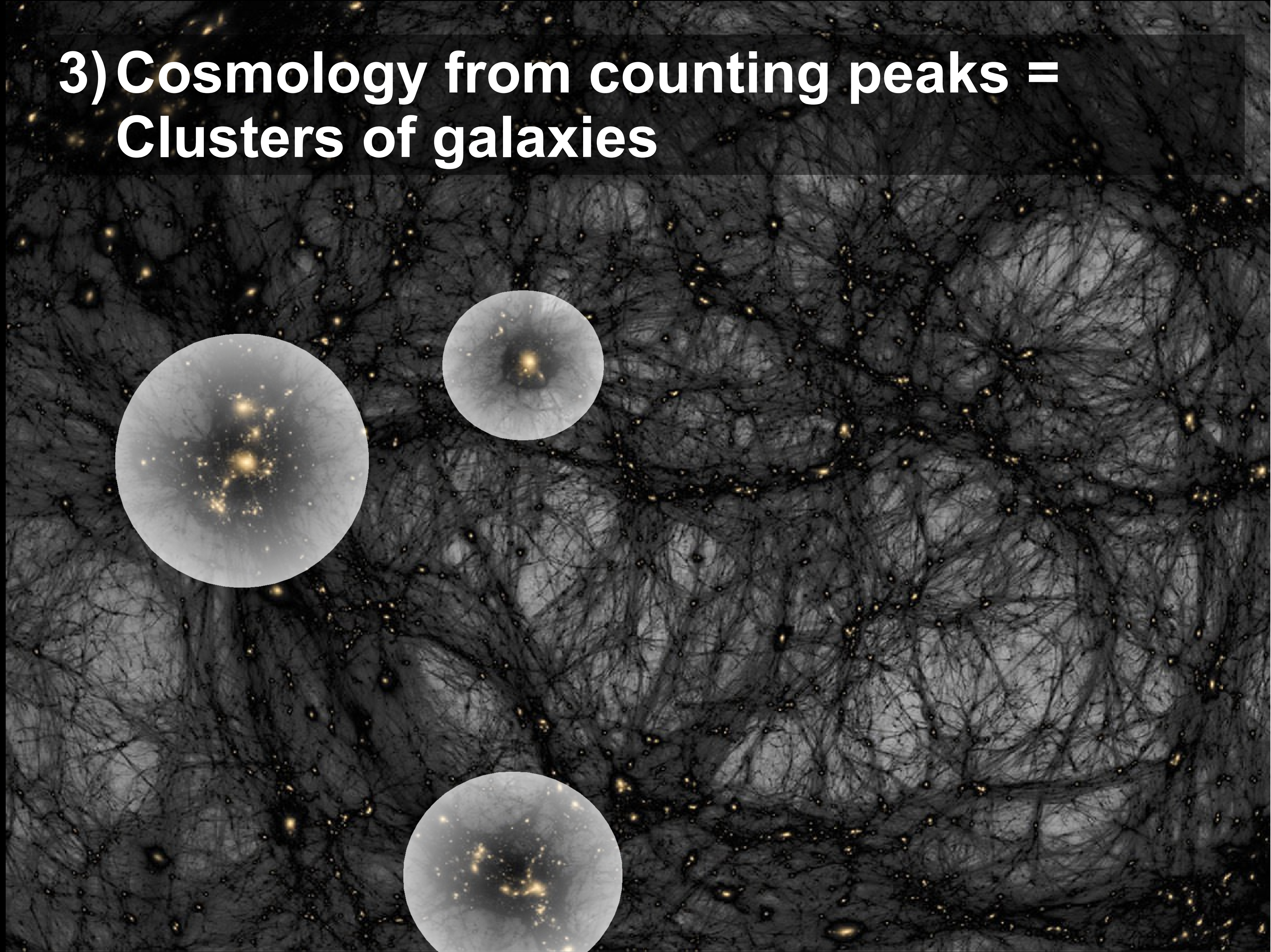
Cosmology from matter/galaxy PDF: skewness of matter density

- Lensing + counts in cells jointly constrain:
  - Cosmology
  - Bias + Stochasticity
  - Skewness of matter density: $S_3 \equiv \frac{\langle \delta^3 \rangle}{\langle \delta^2 \rangle^2}$

- Skewness adds significant constraining power

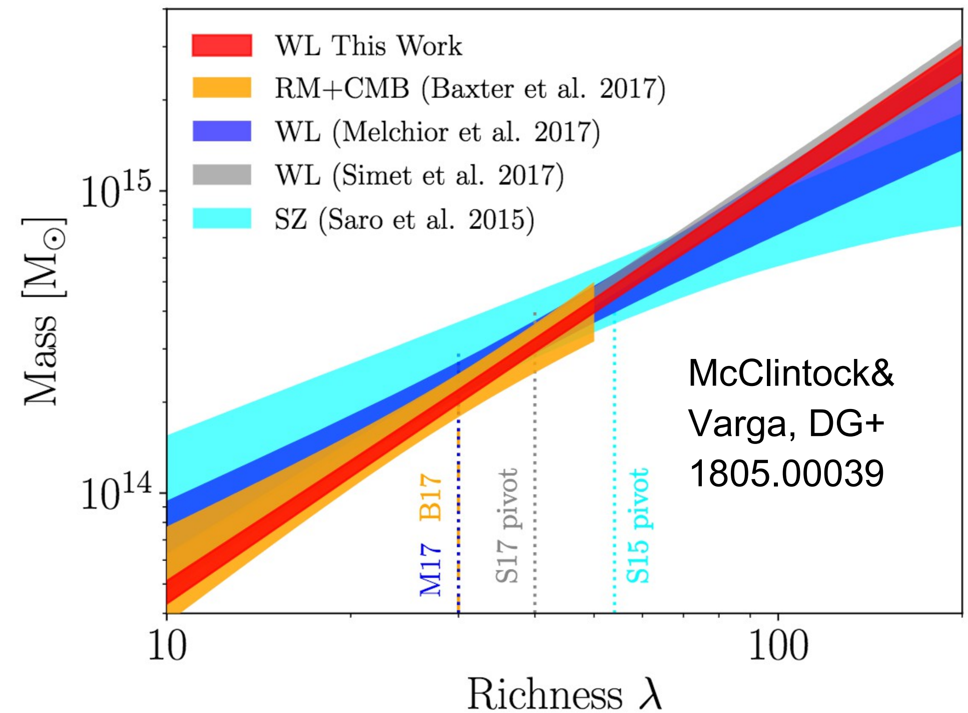


3) Cosmology from counting peaks = Clusters of galaxies



Cluster cosmology requires mass calibration from lensing

- Cluster cosmology is limited by uncertain mass-observable relation (MOR)
- Large area lensing surveys are now by far the best way of calibrating the MOR
- Uncertainties are now limited by modeling and photo-z



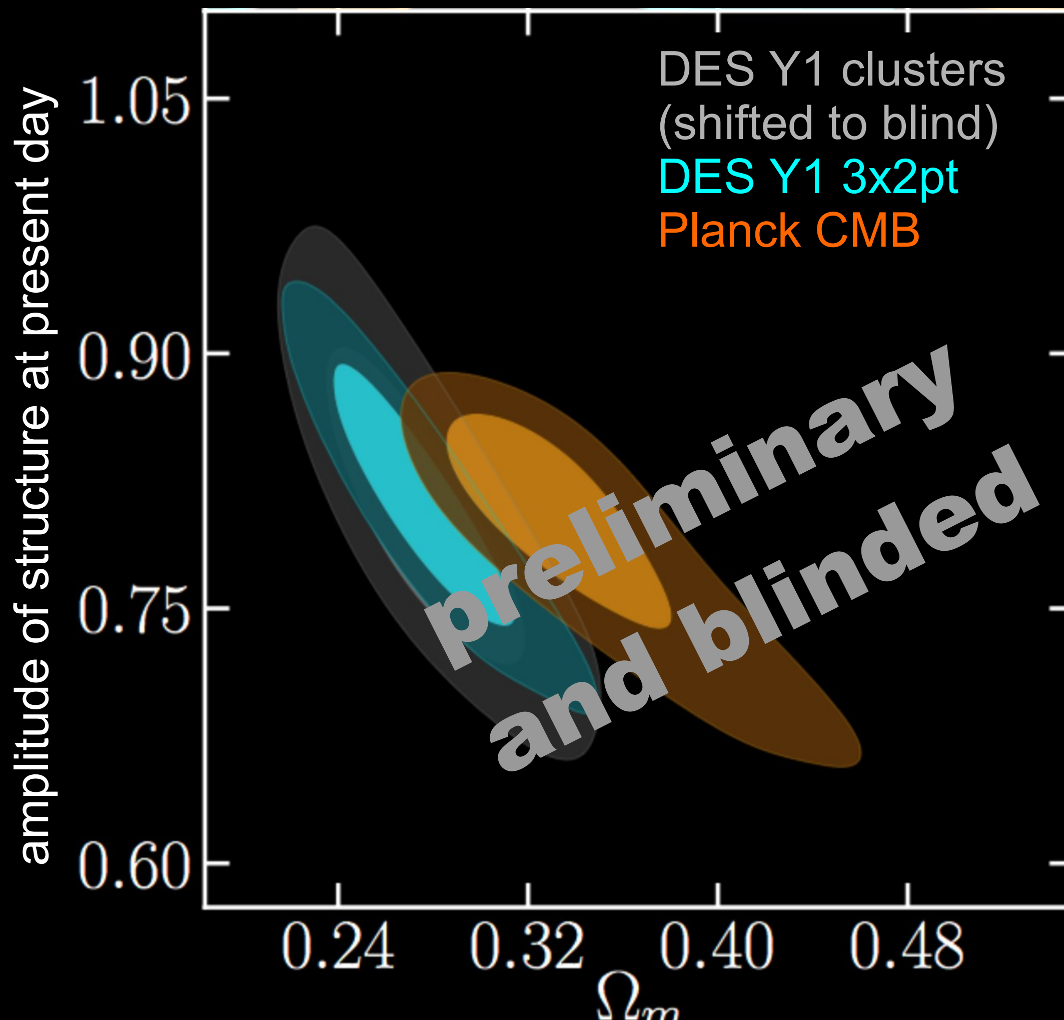
McClintock& Varga, DG+ 1805.00039

Source of systematic	SV Amplitude uncertainty	Y1 Amplitude Uncertainty	
Shear measurement	4%	1.7%	
Photometric redshifts	3%	2.6%	photo-z
Modeling systematics	2%	0.73%	
Cluster triaxiality	2%	2.0%	modeling
Line-of-sight projections	2%	2.0%	
Membership dilution + miscentering	$\leqslant$ 1%	0.78%	
Total Systematics	6.1%	4.3%	
Total Statistical	9.4%	2.4%	
Total	11.2%	5.0%	

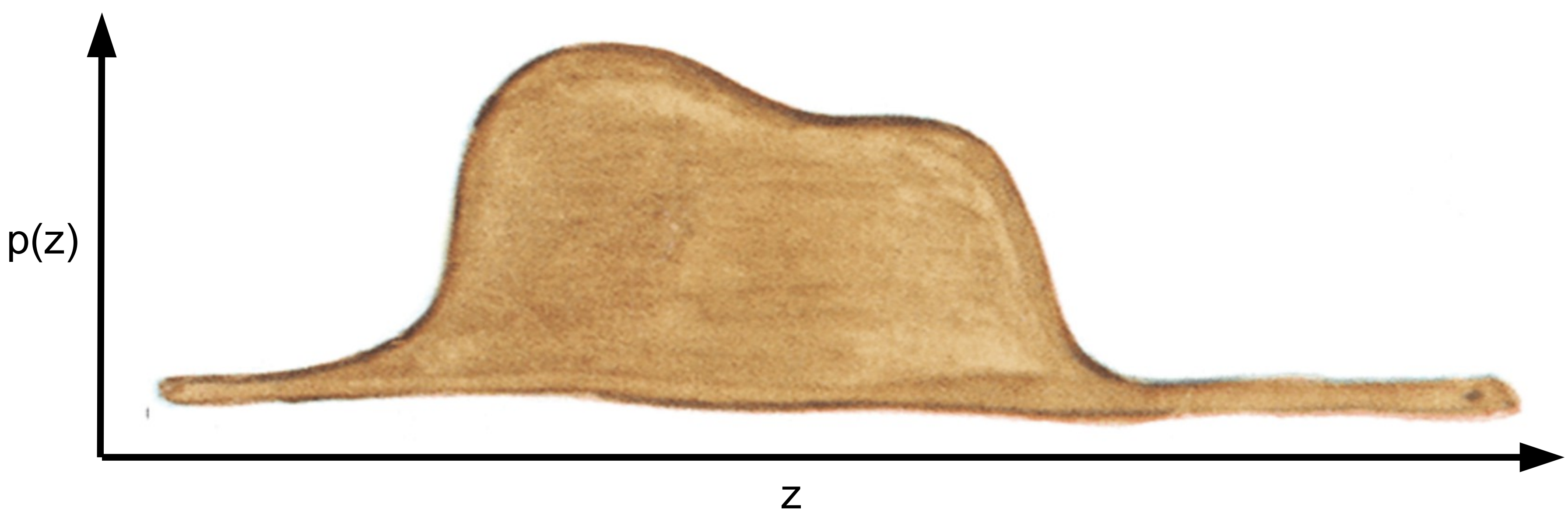
DES Y1 cluster cosmology

Cosmology constraints from clusters in DES Y1

- are competitive with 2pt-functions
- are almost independent from 2pt-functions
- require an X-ray derived prior on mass-observable scatter
- are widened by systematics in lensing calibration



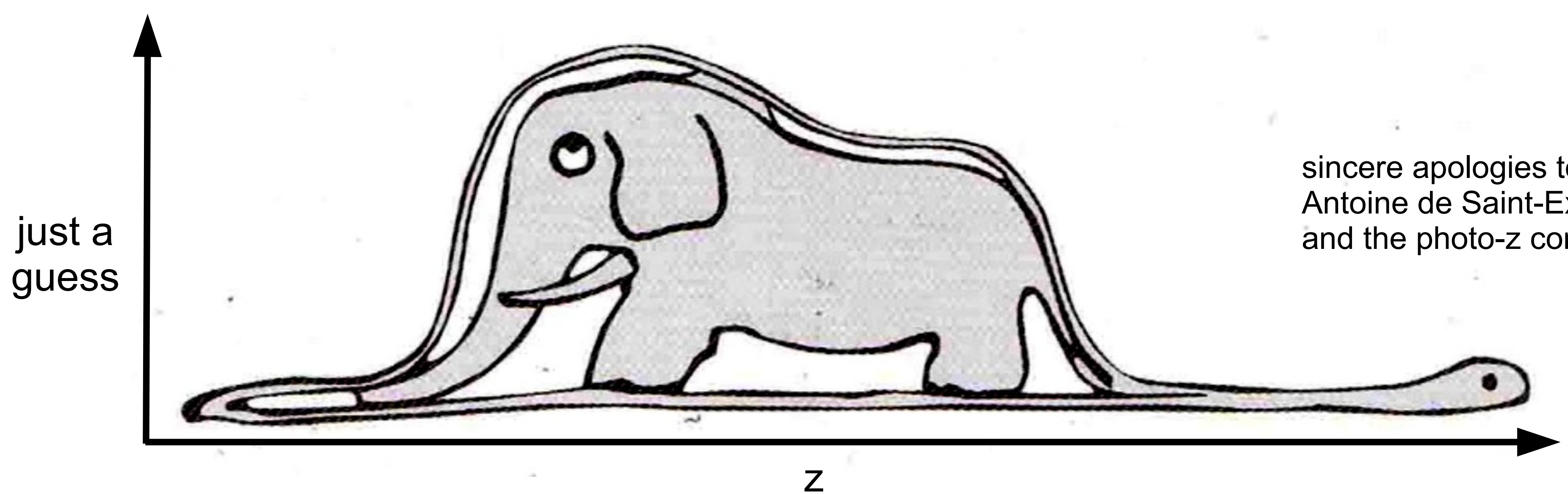
DES+in prep.; see also McClintock, Varga, DG+2018; DG+2018b; Costanzi+2018


p(z)
z

Photometric redshifts are the elephant in the room

There is no “correct” photometric redshift estimate as of today:

- **template fitting** codes make arbitrary choices of templates and priors
  - no estimate for this systematic error – but it's surely O(few %)!
- **machine learning** codes / **spec-z validation** uses non-representative 'truth' sample
  - What is essential is invisible to the eye: these are **selected** by redshift, not just by color/magnitude → biases at O(few %) [Bonnett+2016, DG+2017]



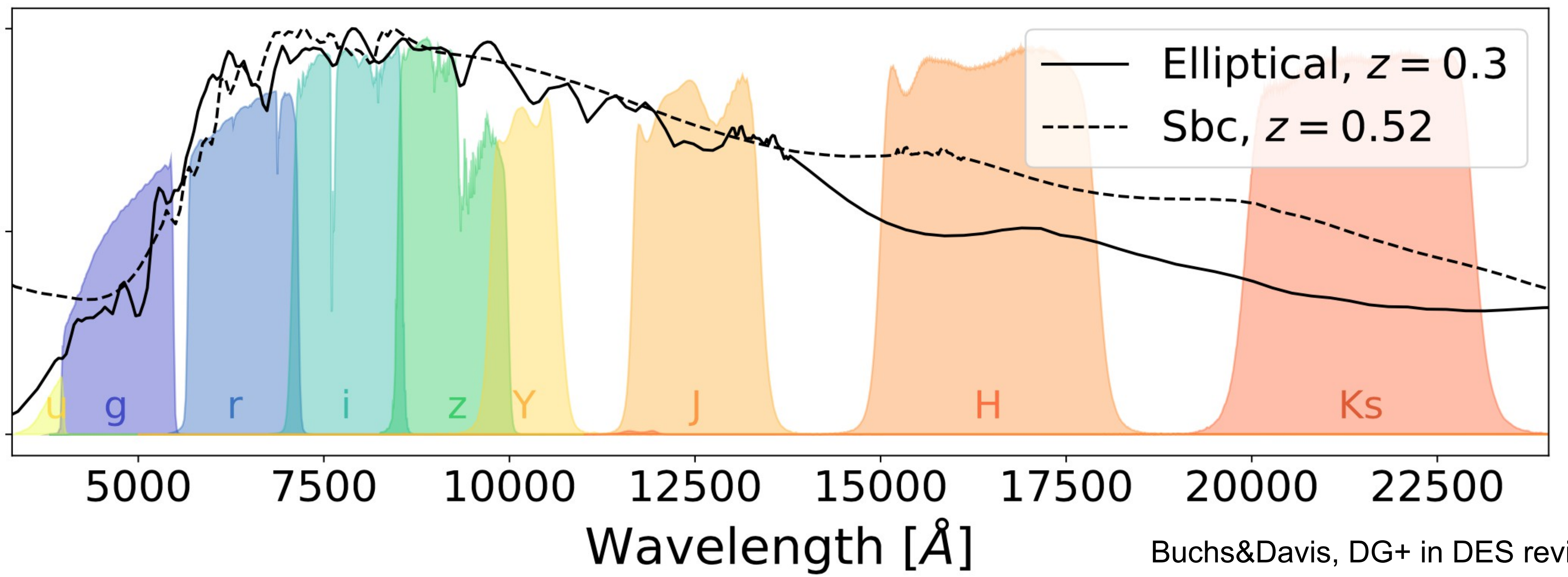
Photometric redshifts are the elephant in the room

see also talk by Boris Leistedt

These are really the same problem: few-band photometry (e.g. r,i,z) does not uniquely determine the redshift/type of a galaxy.

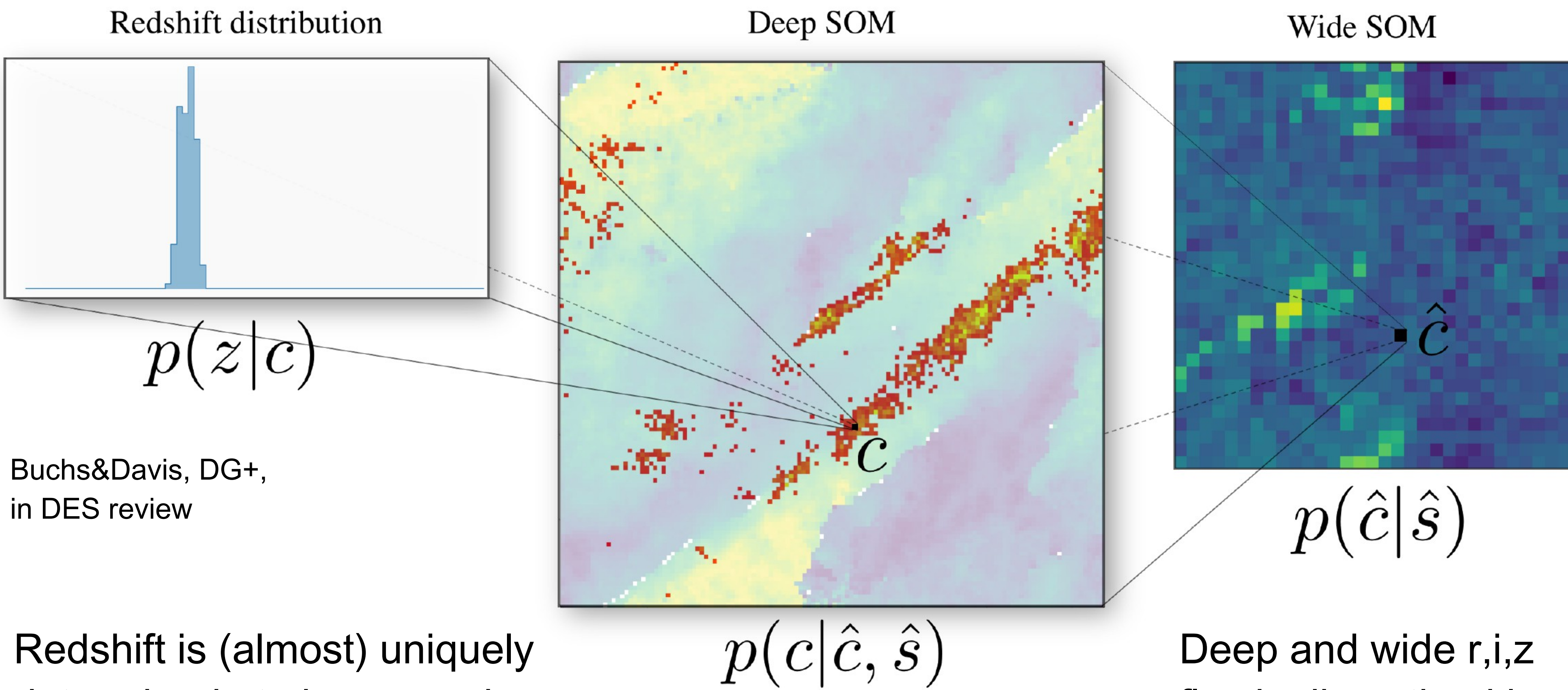
- the wrong prior/template affects estimated redshift distributions
- an additional selection (not reflected in r,i,z) changes redshift distributions
- there is cosmic variance in calibration – a sample of galaxies with the same r,i,z has different redshift at different places in the sky

  The best we can do with r,i,z, and COSMOS is |Δz|~0.02 [DG+2017, Hoyle&DG+2018]



Buchs&Davis, DG+ in DES review

Using, wide, deep, and spec-z fields for Photometric redshift calibration



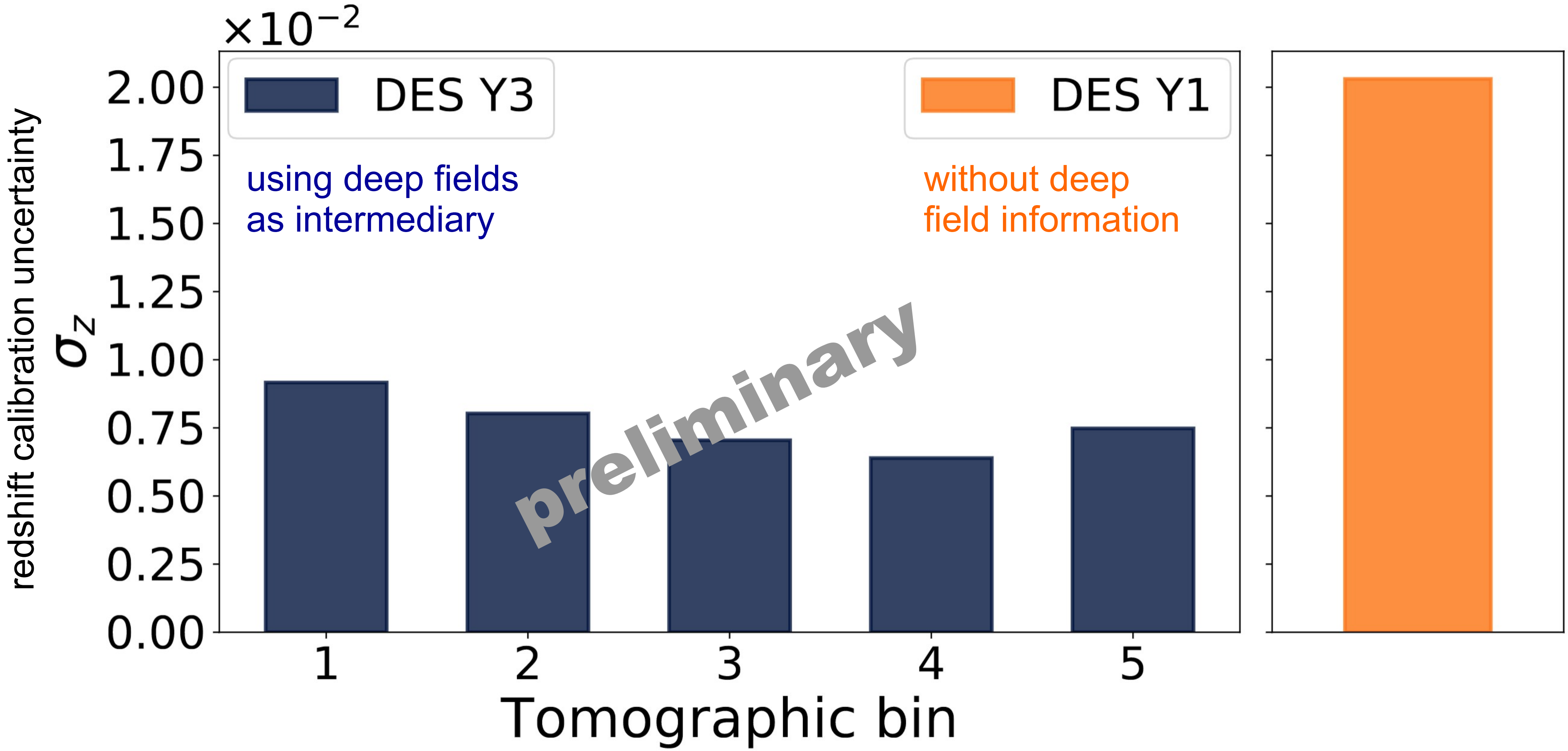
Buchs&Davis, DG+, in DES review

Redshift is (almost) uniquely determined at given u,g,r,i,z, Y,J,H,K, reducing selection bias and cosmic variance from spec-z sample

Large deep sample constrains mix of u,g,Y,J,H,K at given r,i,z to reduce cosmic variance

Deep and wide r,i,z flux is discretized in a self-organizing map to handle survey transfer and selection function.

Using, wide, deep, and spec-z fields for Photometric redshift calibration



Buchs&Davis, DG+, in DES review

In my 5 additional minutes...

- I would like to thank you for the past three years of support. It's been great.
- And note that, with less independent post-doc funding,
  - myself and others might not be here,
  - would have been less able to develop new ideas into an independent research program,
  - or voice a dissenting opinion when necessary,
  - or pass on as much to the next generation of scientists,
  - and certainly I would not have been able to put as much effort and travel into co-leadership of DES.
- I know there are reasons for the cuts, but I doubt they justify the damage caused by reducing independent fellowships. Science requires people with ideas, in addition to instruments.

Summary

- Precise & accurate measurements of cosmic structure with lensing in DES allow multiple, competitive, novel tests of our cosmological model.

  The results are intriguing now and will only get better.

- For the next generation of science to succeed, we will have to improve on systematics, in particular redshift distributions. Use deep field photometry to leverage (scarce) redshift information!

- For the next generation of scientists to succeed, we will need funding for independent post-doctoral fellowships.